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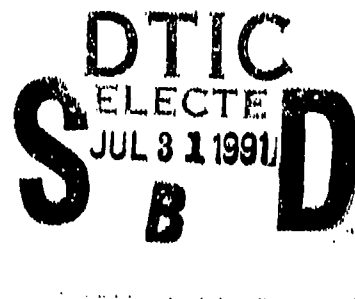
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SUPERWORKSTATIONS FOR TERRAIN VISUALIZATION: A PROSPECTUS

The MITRE Corporation

D. A. Southard

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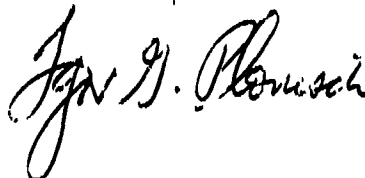
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13. ABSTRACT (Maximum 200 words)
Terrain modeling and visualization is emerging as a key requirement for tactical mission planning, rehearsal, and battle management systems. This study assesses the match between commercial "superworkstation" computers and the needs of deployable unit level systems for these applications. Superworkstations are shown to be functionally well suited to terrain visualization. A prototype terrain visualization system, hosted on a Silicon Graphics IRIS 4D/240GTX workstation is discussed. This prototype demonstrates the concepts developed in this study by exhibiting features such as an "out-the-window" perspective terrain scene synthesized from Defense Mapping Agency (DMA) databases, Landsat images inset into the geometric terrain model, head-up display (HUD) simulation, radar detection envelope representation, haze effects, lighting effects based on time of day and date, and a "God's eye-view" viewport display. Finally, topics for continued investigation into superworkstations and terrain visualization are covered.

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ABSTRACT

Terrain modeling and visualization is emerging as a key requirement for tactical mission planning, rehearsal, and battle management systems. This study assesses the match between commercial "superworkstation" computers and the needs of deployable, unit level systems for these applications. We show that superworkstations are functionally well suited to terrain visualization. We discuss technical issues, and provide examples, in relation to our own superworkstation-based terrain visualization prototype. We identify topics for continued investigation into superworkstations and terrain visualization.

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EXECUTIVE SUMMARY

The trend within the Air Force today is to maximize the use of commercial off-the-shelf (COTS) hardware and software in equipment procurements. Capable computer-based mission planning and rehearsal systems could represent a substantial cost savings, versus training and rehearsal in the field. We see a trend toward increased use of many small, deployable systems to augment a limited number of very capable, but expensive, centralized training and rehearsal facilities. These deployable systems should provide multiple functions, as well as support incremental upgrades and expansions. The lower cost, larger number, and greater availability of such deployable systems could increase overall training and operations effectiveness.

This study compares and contrasts the emerging class of superworkstations to other COTS platforms which might be appropriate for terrain visualization for mission planning and rehearsal. We concentrate on the topic of three dimensional (3D) terrain visualization, in which "out-the-window" perspective scenes are created from digital terrain data bases and photographic imagery. These perspective terrain scenes can be used to explore and rehearse various mission scenarios.

KEY REQUIREMENTS

The chief requirements for terrain visualization in a deployable mission planning and rehearsal system include: perspective view representation of the surface of the terrain with a predefined measure of visual accuracy; visual classification of land use and generic features, such as towns, forests, and fields; mission specific features, landmarks, navigational points; integration of photographic imagery with the underlying geometric terrain database.

TECHNOLOGY ASSESSMENT

We examined the leading hardware and software technologies that could be used for terrain visualization, including computer image generators (CIG), mission planning and digital mapping systems, image computers, general purpose visualization software, geographic information systems (GIS), and current research in computer graphics. We compared and contrasted these capabilities to those which can be hosted by superworkstation platforms. We found that superworkstations are well suited to terrain visualization on the type of deployable mission planning and rehearsal workstations we envision, since they can support not only perspective view terrain visualizations, but also digital mapping and digital imagery applications.

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Much of the current technical effort in terrain visualization has been directed toward creating terrain scenes exclusively from digital imagery. Some of these attempts, however, shortcut the photo-analysis and interpretation stages which are required to construct a detailed terrain database. This practice most likely leads to misleading visualizations. We recommend that digital imagery information should be presented as an inset to, and in the context of, a geometric terrain model derived from a validated terrain database.

TERRAIN VISUALIZATION PROTOTYPE

We constructed a prototype terrain visualization system, based on a Silicon Graphics IRIS 4D/240GTX workstation. This prototype demonstrates the concepts developed in this paper, by exhibiting features such as an "out-the-window" perspective terrain scene synthesized from Defense Mapping Agency (DMA) databases, Landsat images inset into the geometric terrain model, head-up display (HUD) simulation, radar detection envelope representation, haze effects, lighting effects based on time of day and date, and a "God's eye-view" viewport display.

TOPICS FOR FURTHER INVESTIGATION

Although the basic technology for terrain visualization is here, several topics require investigation to articulate and enhance our understanding of the technical issues. The principal technical areas are:

a. Multiprocessing. Software architectures should be developed that effectively take advantage of parallelism inherent in superworkstation hardware.

b. Terrain Modeling. Improvements in scene detail and system response times are possible with the development of advanced data structures for terrain modeling.

c. Complexity Management. A higher overall perception of scene detail and system responsiveness could be achieved by adaptively and dynamically managing the scene content during terrain scene "fly-throughs".

ACKNOWLEDGEMENT

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SECTION 1

INTRODUCTION

Contemporary Air Force procurement programs increasingly encourage the use of commercial off-the-shelf (COTS) hardware and software components in their systems. One aspect of C^3I systems that promises to be most successful in this regard is display system consoles. Commercial graphics workstations offer several features in common with the display consoles used in many Air Force systems.

The commercial graphics workstation market now supports two classes of workstations: engineering workstations, which are characterized by multitasking, multiuser operating systems running on popular microprocessors, monochrome or 256-color bit-mapped graphics displays, a multiwindow user interface, and networking; and "superworkstations" that add parallel- or vector-processing hardware with a tightly coupled, high-performance, full-color graphics subsystem. Whereas engineering workstations are typically used for computer-aided design (CAD), manufacturing (CAM), software engineering (CASE), and electronic publishing, superworkstations are ideal for compute- and display-intensive activities such as interactive visualizations, solid modeling, and simulations. In view of their capabilities, superworkstations would be ideal platforms for C^3I display stations, in situations where hostile environments are not a concern. Combinations of separate vector processor, graphics engine, and minicomputer components, typical of some current C^3I display console designs, are generally not competitive with superworkstations, because of communications bottlenecks and performance mismatches between the various components.

Terrain visualization is a challenging application within C^3I. Terrain is among the central subjects of mission planning and rehearsal, nap-of-the-earth flight simulation, radar modeling, and battle management information systems. We previously built a system for exploring terrain visualization design tradeoffs using a Silicon Graphics IRIS 4D/70GT superworkstation [1]. It featured stereoscopic terrain scenes constructed from DMA elevation and cultural databases. Experience with our evaluation system convinced us that superworkstations are appropriate platforms for many C^3I terrain visualization systems. The system clearly demonstrates that progress in both application software, as well as hardware performance, is required for a really useful capability. Accordingly, we began an effort to improve on our prototype in the following areas:

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a. **Hardware Platform.** We have upgraded our platform to the IRIS 4D/240GTX model, which uses four 25 MHz RISC microprocessor architecture with a nominal 80 MIPS performance level, coupled with a graphics pipeline processor with a nominal 100,000 polygons/second throughput.[1]

b. **Interactive Response.** The current prototype provides a stereoscopic fly-through of terrain scenes with a real-time animation update rate of about 1 frame/second, and perspective views at about 2/second. For best interactive response, however, at least a 5 Hz update rate is required [2].

c. **Scene Detail.** The scenes demonstrated so far contain about 17,000 smooth-shaded triangular facets in each perspective view. At this level, the background details are quite good, but the foreground scene lacks detail. Scene detail can be increased by increasing the number of facets used to model the scene, or by distributing the facets in the scene more effectively. Scene detail is a trade-off with interactive response, since more detail will require more compute and drawing time.

Although we expect continued improvements in hardware capabilities, such improvements will go only part way to the solution. For a complete solution, we also need to make significant progress in terrain modeling techniques.

In the succeeding sections of this document we will:

a. evaluate terrain visualization requirements, propose what is essential, what is optional, and what is extraneous for these applications;

b. gather information on the state of the art in terrain modeling and display;

c. appraise how superworkstations match these conditions;

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[1]Nominal performance numbers are achievable only with optimized synthetic benchmarks; the best performance on a particular application, however, may be considerably less. For a detailed benchmark analysis of several popular workstations, see J. R. Leger, J. L. Conway, and S. J. Hamilton, "Graphics Benchmarks for Real-time C^3 Systems," MTR-10436, The MITRE Corporation, Bedford, MA, April 1989. Superworkstation benchmark results will be found in J. L. Conway, S. J. Freiter and J. R. Leger, "Super Graphics Workstations for Real-Time C^3 Systems," MTR-10894, The MITRE Corporation, Bedford, MA, August 1990.

d. discuss our terrain visualization prototype and selected technical issues;

e. identify areas where advances in software system architectures, terrain modeling, and graphics techniques are needed.

SECTION 2

BACKGROUND

Terrain visualization is an important part of three types of mission-oriented activities: training, planning, and rehearsal.

2.1 TRAINING

In the training phase, a high degree of fidelity to actual mission conditions is important so that skills are correctly transferred. In this arena computer image generators (CIGs) have been and will continue to be dominant. Consequently, these training facilities will remain relatively expensive and centralized. This type of system cannot be stationed at the unit level, moved to forward areas, or installed in moving platforms. Note that for training purposes, it is usually not necessary to model specific areas; a generalized representation is sufficient.

2.2 MISSION PLANNING

Mission planning systems are concerned with automating mission-preparation activities that were traditionally performed manually, with maps, photographs, slide-rules, paper, and pencil. Mission planning today uses primarily a 2D graphics environment, with various maps and charts playing an important role, but with some 3D graphics requirements, such as for static perspective views of terrain. Mission planning applications have been running on systems with microcomputer and engineering work-station components. These systems would be better served by superwork-stations, which have the compute power to handle preflight calculations, as well as graphics power to handle map images, photo images, and perspective views. In addition, superworkstations could make animated, and even interactive perspective scene "fly-throughs" possible. The higher cost of a superworkstation will be mitigated by eliminating the necessity for attached vector and graphics processors, along with their attendant system integration problems.

2.3 MISSION REHEARSAL

In mission rehearsal, there are two classes of requirements. The first class overlaps considerably with the training systems, except that the visual system must model actual, specific locations. We envision such a facility with multi-cockpit, full-fidelity simulators, where teams can

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rehearse and coordinate mission elements under a variety of scenarios and contingencies. In this case, CIGs would be required to support the best fidelity possible. This would be a centralized facility, with crews rotating through for special exercises. Its value would be significant, for example, when preparing for special operations, where some lead time is available.

The second class of mission rehearsal system would be deployable at the unit-level. It could run on the same ruggedized superworkstations used for mission planning. These systems would present partial-fidelity terrain fly-through visualizations. The terrain scenes would be based primarily on preconstructed databases covering the whole world. Local database modifications tools would be available, so that the database could be annotated and updated as conditions change, and as new intelligence comes in.

2.4 REQUIREMENTS

We are specifically concerned with terrain visualization for the class of deployable mission planning and mission rehearsal applications. It is essential to consider the following elements:

a. **Terrain Surface.** The shape of the terrain must be representable to a predefined measure of visual accuracy. The representation should cover the entire field of view that would be visible to the eye from that vantage point. The representation must extend from the foreground, all the way to the horizon.

b. **Cultural Features.** Land use patterns must be easily identifiable. While exact correspondence is unnecessary for generic features, such as trees in a forest, or buildings within a town, there should be specific correspondence for outlines of these areas.

c. **Specific Features.** When certain features have significance to the mission, they must correspond to the actual objects. Examples include any landmarks, navigational points, unusual or identifying features.

d. **Sensors.** The system should be able to generate scenes applicable to different types of sensors, viz. visual, infrared, and radar image visualizations.

e. **Interactive Response.** There should be a "roam" capability, for previewing various routes through the terrain. The update rate should be at least 10 updates a second, to provide for adequate interactive eye-hand coordination with the display controls.

f. **Photo-imagery.** Photographic images, from satellite or aerial reconnaissance sources, should be transformed for viewing from any eye-point.

These items are desirable:

a. **Smooth Animation.** At a minimum rate of 10 Hz, up to 30 Hz updates for smooth motion animation.

b. **Weather and Atmospheric Models.** The effects of clouds, smoke, and precipitation, for example, can be an integral part of mission planning and rehearsal scenarios.

c. **Shadows.** The effects of shadows, either from the sun, moon, or active sensors, have a profound impact on terrain scenes. This problem has, to date, proved intractable for interactive visualizations. There are several techniques, however, that are applicable to static scenes.

SECTION 3

TECHNOLOGY SURVEY

There are a broad range of capabilities available in the spectrum of terrain visualization technologies. An in-depth description of each vendor's offering is beyond the scope of this paper. Instead, we will summarize the important features in each category of product, and provide references to more detailed information. The products and services mentioned in this section by no means comprise a complete list; only major entries in this market are covered.

3.1 COMPUTER IMAGE GENERATORS

The foremost technology in terrain visualization has long been held by companies which construct CIGs for aircraft flight simulation and training [3]. Although CIG systems traditionally are expensive custom installations, CIG architectures are now modularized into standardized components that can be configured for many levels of functionality. Though top-of-the-line systems are still in the multi-million dollar range, low-end versions are now priced around $200,000 [4].

CIG performance is difficult to compare because there is no standard measurement [5]. Performance is usually stated as the number of polygonal faces and lights that can be updated at a certain animation rate. Low-end systems may have a performance of 500 to 1000 faces/update at 30 Hz, whereas high-end systems may update 16000 faces at 60 Hz. In today's systems, these faces are assumed to be textured, antialiased, and shaded with a realistic lighting model, which generally includes at least limited weather effects. This is only a very superficial measure, however, since there are many levels of features and special effects, for example:

a. number of viewpoints, and processing channels
b. number of moving coordinate systems and articulated models
c. number of levels of detail, dynamically managed
d. number of textures supported
e. range of operational area
f. weather and seasonal models
g. weapon models

Recent advances in CIG technology have centered on the use of texture for shading polygon surfaces. Five to ten years ago, texture was generated procedurally, with statistical or frequency-domain models. The last

five years has seen the emergence of generic texture maps, either synthetically or photo derived. This type of texture can be likened to wallpaper, wherein the pattern repeats, but is cunningly matched at the seams to provide a uniform appearance. A basis set of generic textures will handle most terrain scenes. A recent advance has been to use terrain-specific textures, that is, photographic images of the actual location being simulated. This last step has placed enormous demands on database size and management, and system data bandwidth considerations.

We categorize CIG vendors into three tiers. The first tier represents vendors that have defined the state of the art for many years, and which provide a full line of equipment and services [6,7,8]:

a. Evans and Sutherland (CT6 & ESIG-1000)
b. General Electric (CompuScene V & PT2000)
c. Sogitech (GI 10000)

The second tier represents relative newcomers to the market. They include graphics processor and workstation manufacturers who are extending their product lines into image generation, providing competition to the first tier at the low end. We can expect to see more entries in this category in the near future [9,10]:

a. Star Technologies (Graphicon 2000)
b. Megatek (944)

The third tier consists of new approaches to image generation [11]:

a. Hughes (RealScene, HVS)
b. LTV (TopScene)

The third tier entries are interesting in that they abandon polygons, in favor of models based entirely on digital imagery. Various schemes are used to process the imagery to recreate viewpoints other than the viewpoint from which the original image was acquired. These schemes have advantages in the amount of detail, but serious shortcomings, to varying degrees, with regard to the extent and location of the operational area, distortions in the images presented, and fidelity of the scene compared to what would actually be seen at that location. For low-level flights, for example, the 3D extent of trees, buildings and other cultural features may mask features visible from the original camera viewpoint. In this light, it is clear that the use of photographic imagery in no way reduces the requirement for detailed 3D models of terrain and cultural features.

3.2 MISSION PLANNING AND DIGITAL MAPPING

Systems in this category are designed to automate repetitive mission
planning procedures involving maps, such as route selection, and flight
parameter calculations. These systems mainly use digitized pictures of
paper maps as the primary user display; however, these are augmented by
the DMA, Digital Terrain Elevation Data (DTED) and Digital Feature
Analysis Data (DFAD), World Data Bank II, and other databases. Software
modules are provided for route selection, radar display prediction, threat
assessments, and weapons delivery calculations. Some of these systems can
provide a perspective view of the terrain based on SPOT or reconnaissance
imagery. Most of these systems are based on microcomputers like the
MicroVAX II, coupled with a graphics engine. With this type of equipment
it takes about 10 minutes to generate a perspective scene. In some cases,
however, these systems are involved in ongoing improvement programs, which
will extend the capabilities by upgrading the CPU or adding a vector
processing unit. Examples in this category include [12,13]:

    a. General Dynamics (MSS)
    b. Fairchild (MAPS)
    c. McDonnell Douglas (TAMPS)
    d. Harris (DPG)

The Harris DPG product is notable because it can generate real-time
perspective pictures based on DTED and DFAD data. Harris uses digital
signal encoding methods to compress the databases, and a compact set of
specially-designed hardware for display generation. The scenes generated,
however, look quite artificial.

3.3 IMAGE COMPUTERS

Another class of machine used in terrain visualization may be called
image computers, because their architectures are optimized for processing
two-dimensional grids of pixels. Examples include [14,15,16]:

    a. Pixar
    b. VITec-50 Imaging Computer
    c. ATT Pixel Machine

These machines are configured as add-in modules for connection to a
general purpose micro- or mini-computer, either as a plug-in board or a
separate unit. These machines are generally programmable at the firmware
or microcode level, and so provide a complete library of image-processing
functions. In addition they may provide tools for advanced modeling and
ray-tracing. While these systems offer interactive image processing, and

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are used to create photo-realistic scenes, they are generally restricted to off-line generation of movies, due to the computationally-intensive nature of these rendering techniques, and because of the pixel-by-pixel organization of the computations. In contrast, CIGs are organized around polygonal faces, which allow for faster processing, albeit with less "realism".

3.4 GENERAL PURPOSE VISUALIZATION

A number of software products are available which are geared toward flexibility and ease of use in creating graphical interfaces. In many cases these packages feature sophisticated icon/mouse user interfaces to graphical editors for constructing scene elements interactively. Many are equipped with features aimed specifically at the military market. These packages will run on several popular workstations; some may be restricted to one particular manufacturer. Representative of this category are [17,18,19]:

   a. Software Systems (MultiGen)
   b. Gemini Technology (GVS)
   c. Merit Technology (MAGIK)
   d. I.C. Sim (MSS)
   e. Visual Prototypes (VAPS)
   f. CAE Electronics (TIGERS)
   g. ESL (Omniview)

The ESL product differs from the others in that it is designed for creating image-based 3D scenes. The others are oriented towards polygons.

These products are best for rapid prototyping, engineering evaluations, or one-of-a-kind applications. For production applications, however, the generality of the underlying data model can hamper efficient processing. Due to the relatively long time required to develop, market, and support software applications, these systems rarely seem to take advantage of the latest workstation capabilities. Although "hooks" are included for extensions to the packages' functionality, it can be awkward or impossible to include a class of extensions that was not foreseen by the product's designers.

3.5 GEOGRAPHIC INFORMATION SYSTEMS (GISs)

GISs are used by architects, engineers, cartographers, and geoscientist in applications such as land use surveys, environmental impact planning, mapping, and watershed analysis. A few of these systems are listed below [20,21]:

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a. Grass
b. Environmental Research Institute (ARC/INFO)
c. MapInfo (MapInfo)
d. GeoVision
e. Intergragh
f. Erdas

Although there is no universal model, GISs usually organize data into layers. Each layer is a grid of values. Each layer represents a specific property or data type: lakes, roads, tree cover, terrain elevation, etc. Various operations are allowed to synthesize new layers by combining existing layers, and for overlaying various layers to create a map. Although some systems do calculate perspective views based on terrain elevations, this is a perspective view of a "draped" map, with symbology flattened onto the terrain surface, since there is no attempt to provide 3D models of the underlying features.

3.6 COMPUTER GRAPHICS RESEARCH

There has been much activity in computer graphics devoted to rendering terrain scenes, but these are nearly always devoted to imaginary terrains, either developed for modeling physical processes, or as elements in animation sequences. A few reports provoke special interest. Several student projects originating at the Naval Postgraduate School have illustrated the utility of superworkstations for command and control visualizations [22,23]. One paper describes the application of a montage of aerial photographs to the terrain surface, creating perspective views used for environmental assessment [24]. Another presents a range of visualization techniques applicable to GISs, which would be of interest for mission planning activities [25].

The literature also provides a number of good ideas for alternative data structures, which can be used for structuring databases and displaylists. Top candidates include:

a. Quadtrees. The quadtree is a structure for storing images [26]. Among its advantages: it can compress areas of redundant pixels; its hierarchical structure adapts well to storing multiple levels of image resolution; the quadtree concept can be extended for organizing other types of data. Quadtrees are, however, somewhat inflexible, due to their rigid decomposition structure.

b. Delaunay Tree. This hierarchical structure stores multiple levels of triangulations for surface models [27]. A triangulated structure is flexible, and eliminates redundant data. It does have some attendant costs due to its irregular nature. It is well suited to terrain surface modeling, and for graphics rendering.

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The CIG manufacturers have done more work in terrain visualization than anyone else, but because of competitive pressures, they make only very general statements about their technology in the open literature. There are suggestions, however, regarding some interesting future developments [28]:

a. **Dynamic Instantiation of Generic Features.** Currently, all features in a terrain scene must be explicitly modeled. Aggregate features, like forests, are usually modeled with texture-mapped areas, since it would be far too costly to model each tree individually. A new approach would be to model an area statistically, then instantiate individual trees on the fly, as needed, for foreground detail. This technique could also be used to create a high degree of 3D detail in towns, where individual buildings are generally not mission-critical, but the overall distribution and layout is.

b. **Continuum of Levels of Detail (LOD).** Conventionally, terrain is modeled at a few levels of detail, with the lower levels fading to higher levels as the distance from the viewpoint decreases. The more LOD, the better the representation adheres to a given visual discrepancy tolerance. Furthermore, the storage expense is only marginally greater than the small LOD models, and the performance benefits should be significant.

For superworkstation based systems, development should be focused on each of the areas described here. Of critical importance is the identification of an appropriate hierarchical data structure that supports terrain visualization requirements [29]. A successful architecture will likely be a hybrid, combining features of both quadtree and Delaunay tree structures. To display the terrain information effectively, techniques must be developed for dynamic instantiation of bulk features, and for incremental transitions between many levels of detail.

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SECTION 4

ASSESSMENT OF CURRENT TECHNOLOGY AND TRENDS

In this section we will evaluate the current technology and trends, and consider how superworkstations could meet the demands of terrain visualization.

4.1 PHOTO-BASED VERSUS GEOMETRY-BASED ARCHITECTURES

Based on the natural desire to achieve the greatest detail possible, there is a great temptation to base terrain visualizations entirely on photographic imagery. Although it is absolutely essential to incorporate imagery into terrain visualizations, basing the entire system structure on images alone introduces severe difficulties.

The advantages of photo imagery are clear:

a. Widely Used. Aerial and satellite photographs are indispensable tools for terrain analysis, they are well understood, and perceived as "real data".

b. Detailed. The detail contained in photo imagery is difficult to produce by any other means.

c. Timely. Satellite imagery and reconnaissance photographs provide up-to-date information.

When applied to perspective view terrain visualization, however, images pose some difficult problems:

a. Inflexibility. The conditions at the time of acquisition are frozen in the image. Visualization of alternative time of day, season, or weather conditions is difficult. Simulations of alternate sensors, such as infrared or radar may not be possible.

b. Distortions. When transformed to an alternate viewpoint, the geometric distortions introduced can become objectionable. The visibility of certain objects may be indicated falsely [11].

c. Interpretation. Sometimes photos are open to diverse interpretations; an expert in this field may be required to make a correct assessment.

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d. **Resolution.** When viewed in perspective, foreground pixels can become enlarged until they are unrecognizable, blurry blotches.

e. **Underlying Model.** If there is no underlying 3D model, the photo elements will appear to be flattened onto the terrain surface. These appear as overhead views of buildings and trees "pasted" onto the ground.

f. **Storage and Data Bandwidth.** Images can place an enormous burden on a workstation's resources. For example, to get good foreground detail in a low-level fly-through visualization, one would need image resolution of at most 1 foot between pixels. Readily available data like Landsat and SPOT are only 30m and 10m, respectively. This means that aerial photographs must be used. Aerial photographs require much more image warping for the perspective transformation, because the shape of the terrain is now significant with respect to the sensor location and orientation. Also, stereo photos would be required to get a correspondingly detailed terrain elevation model. Complete coverage of a practical area of interest would be difficult to obtain, and if obtained, would be enormous to manage.

The alternative to a photo-based structure is to synthesize the scene from a database of 3D models. This is the approach taken by all major CIG systems. The advantages to this approach include:

a. **Flexibility.** Various conditions, such as time of day, season, sensor characteristics, and late intelligence, can be incorporated into the visualization database, and options can be selected at will.

b. **Sharpness.** Cultural features, such as buildings and towers, are rendered clearly, without the fuzziness associated with magnified photographs.

c. **Databases.** The databases can be constructed automatically from existing databases, and automated tools can be used to augment existing databases where required.

Synthetic models, too, have their shortcomings:

a. **Detail.** The synthetic images can be severely lacking in detail [30], lending a "cartoon" impression. This objection can be ameliorated by application of shading and texture mapping techniques to 2D surfaces, and automatic instantiation of generic features for aggregate objects.

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b. **Data Acquisition.** The databases are difficult to construct from scratch. This process, however, is amenable to automated tools, and advances in computer vision will eventually lead to automated database construction from the raw data, photographs and maps [31].

c. **Timeliness.** Current databases have been processed from original information that is years old. It would be essential to include means for updating databases with missing or new information.

Although databases are ultimately derived from photographic imagery, it is advisable to base a visualization system's architecture on the interpreted form rather than the raw data. Images can be properly incorporated either as photo-derived textures for the 3D model [32], or as an overlay or inset in mission-critical areas.

4.2 SUPERWORKSTATION CAPABILITIES AND LIMITATIONS

Superworkstations have several strengths:

a. Fast drawing of polygonal meshes, either Gouraud or flat shaded;

b. Significant integer and floating-point processing capacity;

c. Multiprocessing/multiprocessors;

d. Network connectivity.

For terrain visualization, they lack:

a. Texture mapping hardware support
b. Real-time antialiasing
c. Image processing hardware
d. I/O channel bandwidth

For the most part, these shortcomings will diminish with time. The best strategy will be to capitalize on the superworkstations' strengths, by concentrating on fundamental problems that will not be altered by maturing hardware technology.

Workstation and graphics processor vendors have just released a new generation of products aimed at applications previously reserved for CIGs. To compete in this market, this new generation of workstations boasts shaded polygon throughput rates exceeding 500,000/second, and fast frame

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buffer clears to support update rates up to 30 Hz. These image generator/superworkstations will have CIG-like features such as texture mapping, antialiasing, and haze or fog effects. This step in itself will improve scene detail, to a degree.

Texture mapping support, however, will not immediately solve the imagery-draping problem. The texture map will be limited to a relatively small size, precluding its use for draping images over extended areas. In this case, 3D photos must be rendered using polygon meshes. A back-of-the-envelope calculation illustrates the limits of superworkstation capabilities for animation of photographic scenes: An ideal use of display resolution would evenly tile the display screen into about 64K triangular faces. Assuming a low-level flight scenario, this would correspond to a foreground image resolution of about 1 foot. If we multiply the number of faces by 2 to account for occulted and back-facing tiles (presumably handled by Z-buffer), we get 128K faces. At a 15 Hz frame update rate, we have 1.9M faces/second actual throughput. Multiply by 2 again for implementation inefficiencies, and we need a workstation nominally rated at 3.8M shaded faces/second throughput. Assuming a 4x improvement per generation, this level is about two generations ahead of today's superworkstation technology. Assuming a generation every 2 years, this point lies about 4 years in the future. For the time being, photo-presentations will be restricted to lower resolution and/or lower update dates.

A recent study [33] suggests that for low-level flight simulations, the density of 3D objects is more important than the details in the individual objects. Spatial judgments are based only partly on 2D details; the 3D content on the scene is equally important. This result supports the idea of dynamic generation of 3D objects within bulk features, like forests and towns. Also, since texture mapping is likely to exact a performance penalty in superworkstation platforms, it will be important to use this capability judiciously. The best use will be to allocate the texture mapping to a few mission-critical objects, and use a high density of simple generic objects in other areas.

CIGs have long used a pipeline architecture to increase throughput. Since interactive graphics programs do not vectorize well, the best way to use a superworkstation's multiple processors will be to follow the example of CIGs, and organize programs into a pipeline. This means having several independent, cooperating processes. Conceptually, the processes are synchronized by passing data tokens to the next process. This communication could be implemented using message passing or shared memory. If certain stages of the pipeline might become blocked, by I/O for example, multiple copies of that stage's process could be available to run on another piece of the problem while one process is waiting. The goal is to

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balance the number of processes, and the amount of work in each, so that all the CPUs, and the graphics processing unit, remain highly utilized, without incurring excessive process switching costs.

In terms of graphics hardware performance, superworkstations are roughly equivalent to CIG of about 10 years ago. There is no parallel advancement, however, in terms of "complexity management" structures. We need to look at effective ways to move CIG complexity management strategies to superworkstation platforms.

SECTION 5

TERRAIN VISUALIZATION PROTOTYPE

This section describes the extensions and enhancements that we have made to a terrain visualization prototype, which we described in [1]. This prototype focuses on 3D perspective visualization of terrain databases derived from DMA, DTED and DFAD. The system provides for 3D stereoscopic displays of "out-the-window" terrain views. The software runs on a Silicon Graphics IRIS 4D/240GTX superworkstation. This prototype demonstrates some of the concepts described in previous sections of this report. In particular, we will discuss the improvements and implementation issues regarding:

a. methods for integrating satellite imagery of select areas into the geometric terrain model;

b. representation in 3D space of sensor detection envelopes;

c. simulation of a head-up display (HUD) on stereoscopic computer displays;

d. simulation of atmospheric effects on visibility;

e. cartographic "God's eye-view" display.

5.1 SATELLITE IMAGERY

Integration of satellite imagery into perspective terrain scenes is one of the most challenging tasks for superworkstation based systems. Until recently, this task could only be attempted by expensive and proprietary CIG systems. Now, low-end CIG and superworkstations are available. These systems include texture mapping capabilities. Unfortunately, the texture maps of these systems are limited to a maximum size of about 256 x 256 pixels. While this is adequate for generic textures that repeat themselves to tile a surface, this size of image represents only a very limited ground area. For example, a Landsat image of those dimensions represents only 59 km^2; a SPOT image would cover only about 7 km^2. In contrast, an area of interest could easily cover over 10,000 km^2.

Our approach to this problem is to transform the image to a polygonal mesh, which can be rendered efficiently by superworkstation platforms. The idea here is that each vertex in the polygonal mesh contains a color

and a 3D coordinate. The mesh tiles the image so that the aggregate mesh reconstructs the appearance of the image. The advantage of this approach is that it integrates the entire terrain model into the polygonal database. This is a great simplification. The disadvantage is the negative effect it has on storage requirements. Images, due to their implicit grid structure, can be stored efficiently as an array of numbers. Coordinates for geometrical primitives, like polygons, however, must always be explicitly stored. We mitigate this somewhat by eliminating some of the redundant information contained in the imagery.

5.1.1 Image Registration and Resampling

Landsat imagery is usually processed using a Space Oblique projection, in which the image axes are not aligned along north-south and east-west directions. Our visualization prototype, however, is based on DMA, DTED and DFAD databases, which use a latitude/ longitude/elevation spherical coordinate system. In order to integrate satellite imagery into this visualization, it is necessary to transform the image into latitude/ longitude coordinates. This process is called image registration.

Landsat imagery has a ground resolution of about 28.5 m between pixels. (See figure 1.) At this relatively coarse resolution, we were able to use a simple image scaling and rotation scheme that provides adequate registration. We identified features in the DFAD database that correlated to the image, and used these as alignment control points. Together with a latitude/longitude reference point provided in the Landsat data, we could determine a scaling and a rotation factor.

This technique is really adequate only for demonstration purposes; in an actual system, a more sophisticated technique would be required to match the image to the geometric database. Images of finer resolution, such as SPOT images, which have a ground resolution of about 10 m between pixels, would also require improved techniques, such as quadratic warping, to eliminate image distortions.

Once the resampling has occurred, the image is registered to latitude/longitude coordinates, and it is relatively straightforward to look up the elevation for each point in the DTED database. Since images have much finer resolution than the DTED database, we used bi-linear interpolation to obtain elevations for image points that lie between DTED grid points.

5.1.2 Visual Image Construction

The images supplied by the Landsat Thematic Mapper (TM) sensors are acquired in seven spectral bands, ranging from visible blue-green to the far infrared. The TM sensors were designed for detecting different types
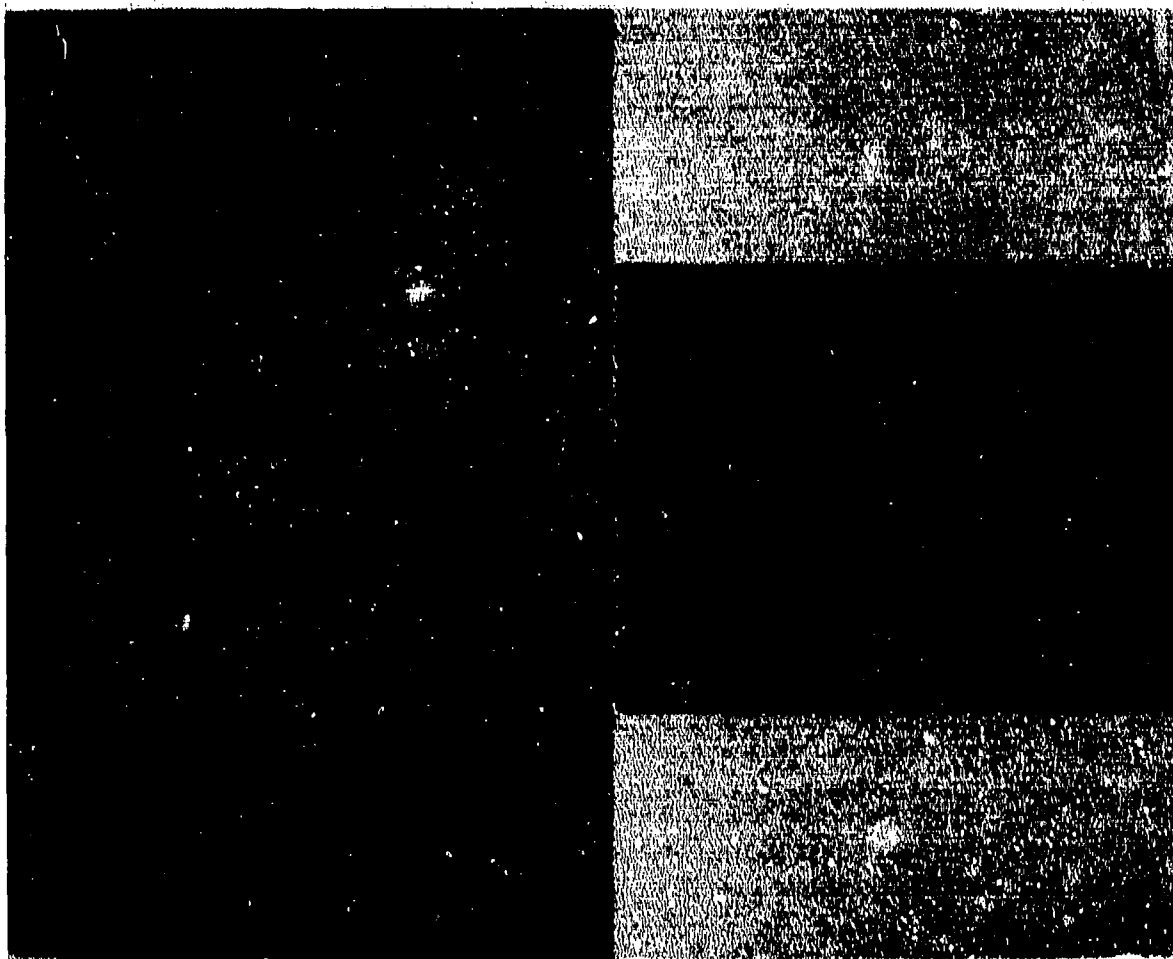
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Figure 1.   Landsat Imagery.   On the right, an overview of a Landsat image
quadrant.   On the left, a magnification showing the level of
detail represented by 28.5m resolution images.

of vegetation and land usages. We wished, however, to recreate a visual image of the terrain. The TM data are not ideally suited for this purpose, but a reasonable visual reproduction can be obtained from the first three bands of TM data. Band 1 records blue-green, band 2 records green-yellow, and band 3 records red. (See figure 2.) Each band is recorded as an 8-bit value that ranges from 0 to 255.

The first pitfall when combining these three bands into a red-green-blue (RGB) color image, however, is to take the data as is, using band 1 as blue, band 2 as green, and band 3 as red. The various bands, however, are acquired by different sensor banks, and each band is actually recorded in different radiometric units. Scaling and offset parameters for each band are provided in the Landsat information records, which allows us to transform the bands into consistent units. Since most uses of Landsat data are concerned only with creating pseudo-color images of various infrared bands, this requirement is generally not acknowledged in the Landsat literature.

Even after radiometric correction, there is yet another pitfall. The TM sensor spectral bands do not correspond to the phosphor colors generally found on RGB color monitors. TM data displayed as RGB will exhibit a color shift. There are methods, however, which can be used to convert from one set of tristimulus values to another using linear transformations [34,35]. Colors can be measured in absolute terms by using CIE 1931 chromaticity coordinates (x,y,Y). These coordinates may be measured for display devices using a chromaticity meter. Unfortunately, the chromaticity coordinates for the Landsat spectral bands are not generally available. We could not obtain this information from EOSAT, the company that acquires and distributes Landsat data. The chromaticity coordinates could be calculated from the precise shape of the spectral response curves for each band, but again we found this information to be unavailable. We recommend that future efforts to reconstruct color visual images from Landsat data obtain the spectral response curves from the satellite manufacturer, so that a proper visual reconstruction can be calculated.

5.1.3 Spatial Filtering for Multiple Levels of Detail

The area represented by one pixel in a perspective scene varies considerably from the foreground to the background of a scene. For example, at a height of 30 m above ground level, the spacing between foreground pixels is about 6 cm; at the horizon, which could be as far as 20 km away, the pixel spacing is about 5 m. Since the field of view is roughly shaped like a thin triangle, with the viewpoint at the apex, the amount of area in the foreground is quite small compared to the area covered in the background. These facts have several consequences:
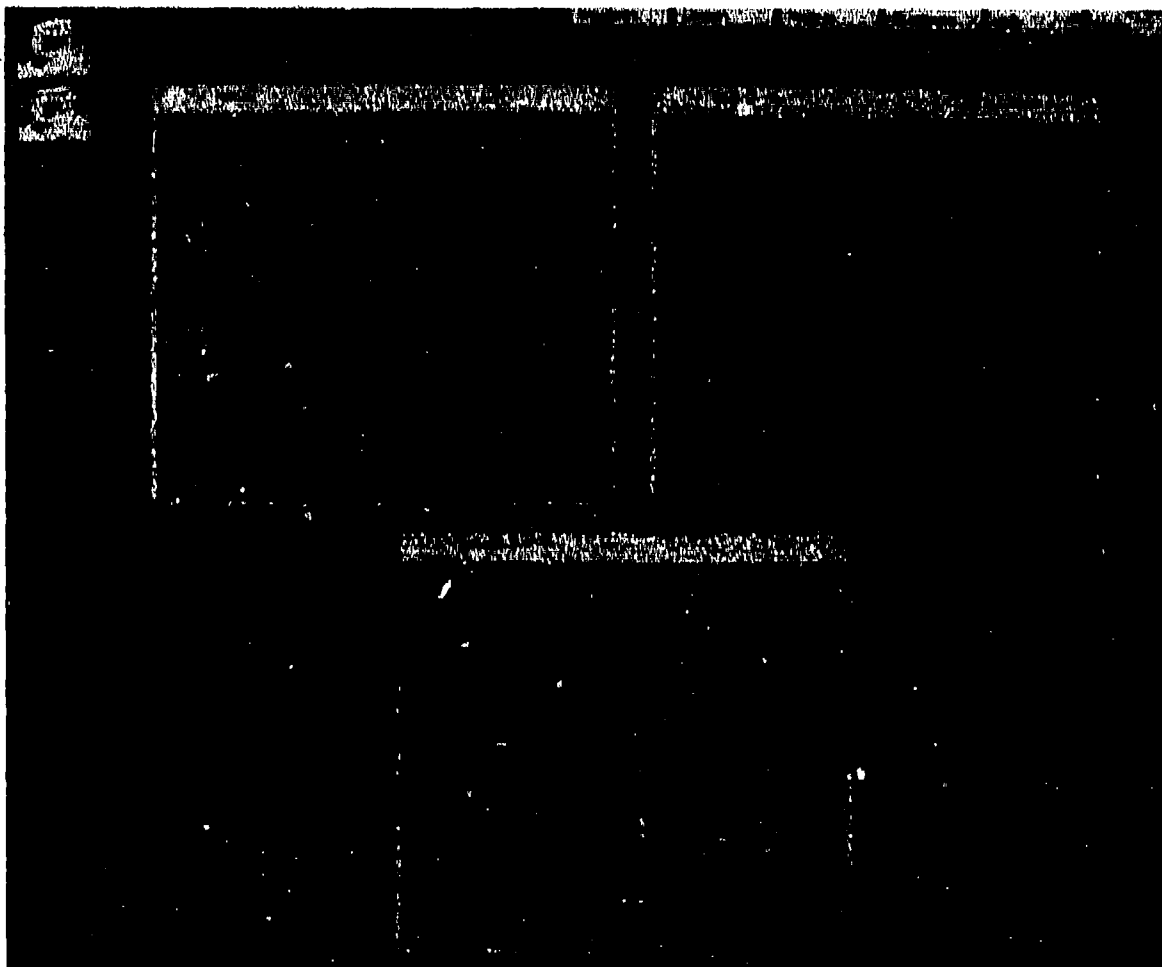
24

Figure 2. Landsat Visible Spectrum Bands. Band 1 represents blue-green,
band 2 represents green-yellow, and band 3 represents red.

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a. The foreground of the scene must be much more detailed, in
    absolute terms, than the background.

b. An image ground resolution of less than 5 m would lead to an
    aliasing effect in the background.

c. All but the most highly detailed aerial photographs will appear
    fuzzy in the foreground.

d. If the same image resolution is used for the entire scene, an
    inconsistent image quality will result. Foreground: fuzzy;
    middle ground: detailed; background: aliased.

e. Due to the large area of coverage in the background, using the
    image data for the entire scene is prohibitive in terms of both
    storage requirements and response time.

As a result of these considerations, we selected a few terrain
patches as a "target area" for satellite image "draping". Each terrain
patch represent about 28 km^2. We have also adopted a "pyramid" data
structure for these patches. The pyramid structure is illustrated by
figure 3. The pyramid is created by filtering the original image with a
low-pass digital filter, then resampling the image so that each dimension
is reduced by half. This process can be iterated until the desired number
of levels is obtained. Each filtered level requires 1/4 of the storage of
its previous level. By pre-filtering in this fashion, the original de-
tailed image can be used only when required for the foreground of the
terrain scene. The filtered levels are selected as appropriate by the
complexity management algorithm, with the most highly filtered versions
used when the patch is distant from the viewer's location.

In our prototype we used up to four levels in the pyramid. The
Landsat data are coarse enough so that aliasing would really not be a
problem, but this technique did improve the response time performance, and
maintained subjective image consistency from foreground to background.

5.1.4 Construction of Tessellated Image

Once the image has been filtered and resampled, creating a pyramid
image structure, the final step is to transform the image into a polygonal
mesh. The straightforward technique is to assign each image point to a
triangular mesh. By Gouraud shading this polygonal mesh, colors for the
spaces between the actual pixel locations will be interpolated. If there
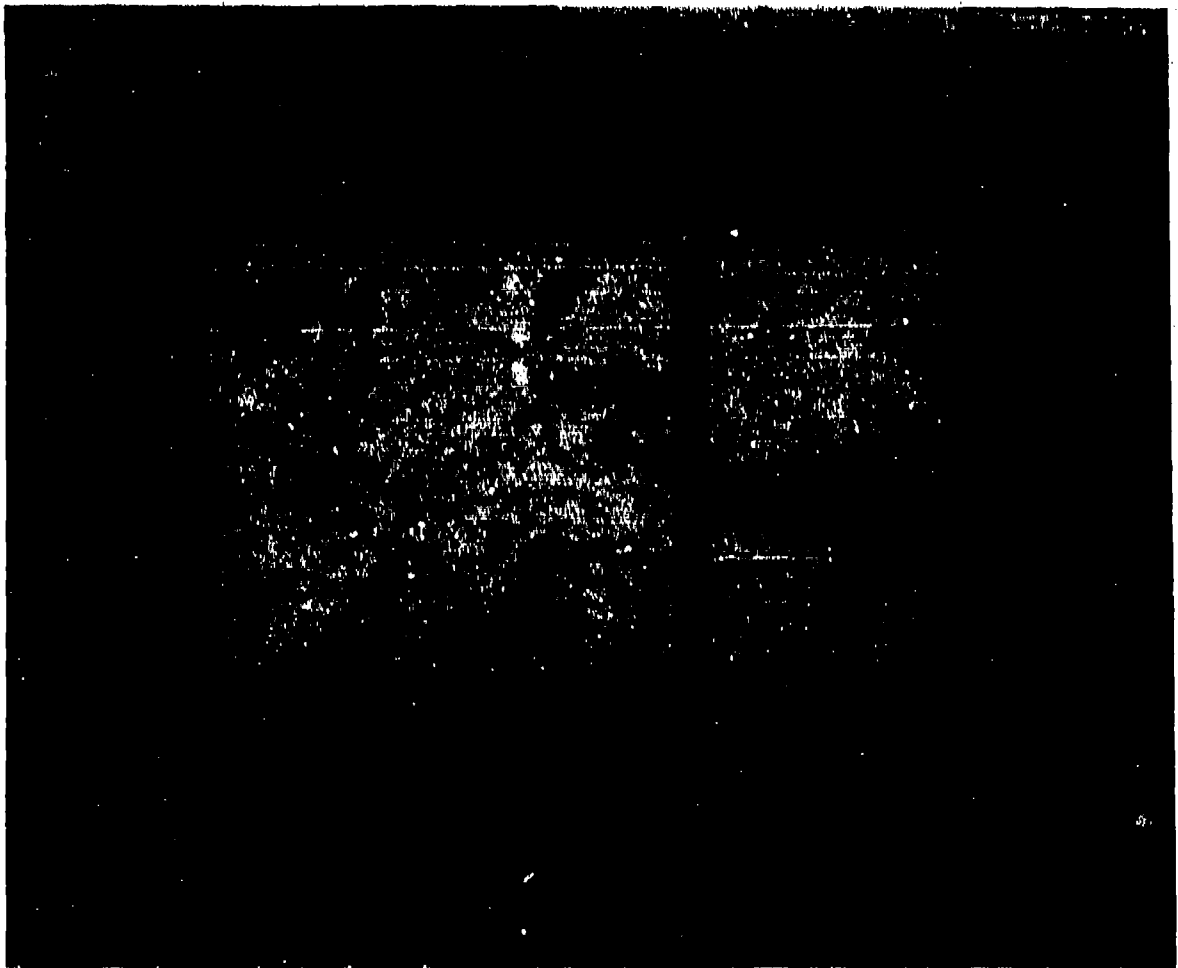are n pixels in the image, this technique will generate approximately $2n$
polygons.

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Figure 3. Image Pyramid. RGB image at four resolutions

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(a) Overhead View

(b) Oblique View

Figure 4. Tessellated Image. Perspective views of a reconstructed 3D image tessellation.

Figure 5. Terrain Visualization with Landsat Image Inset

5.2 SENSOR DETECTION ENVELOPES

One obstacle that 3D displays must overcome in the C^3I environment is the display of abstract, annotational, or amplifying data. On a 2D map display it has become natural to introduce various kinds of overlays for this purpose. This practice offers no difficulties for comprehension beyond the abstraction required by the map itself. Viewers of 3D perspective displays, on the other hand, are not used to such abstractions in a perspective scene. The result is that straightforward extensions of 2D practices to 3D displays may be less than effective.

We undertook to represent the detection envelope of a radar, accounting for the masking properties of the terrain with respect to the radar location. Conceptually, the radar can detect a target with certain characteristics, such as those of an aircraft, within an irregularly shaped volume. The size and shape of the volume primarily depend on the characteristics of the target, the radar's location with respect to the shape of the terrain, and the characteristics of the radar itself. Assuming that all these factors can be modeled adequately, we seek an effective way to render this volume in a 3D perspective scene.

At first we attempted to model the surface of the volume using a wire-frame rendition [1; p. 49], but we quickly found this technique to be inadequate for perspective scenes. The lines representing the foreground and background portion of the surface could not be distinguished, and in general contributed to a very cluttered appearance, which was incongruous with the rest of the terrain scene.

After experimentation, we have concluded that this type of display information must be designed with a clear physical analog in mind. Our final solution attempts to represent the radar detection volume as a translucent, crystalline material, and is illustrated in figure 6. An ideal rendering would require ray-tracing, but for this real-time application we adopted simpler techniques. The surface of the volume is modeled as a polygonal mesh, using Gouraud shading combined with a Phong lighting model of the sun's illumination. A specular lighting component similar to that used for metallic materials was found to be effective. To simulate the translucency, the pixel fill pattern was set to a "checkerboard" halftone pattern. This combination provides for an effective impression of the shape of the volume, provided by the lighting model, without entirely obscuring the objects behind this volume.

5.3 HEAD-UP DISPLAY

Head-up displays provide a pilot with critical information without requiring him to look down at his instruments. Our version of a simple,
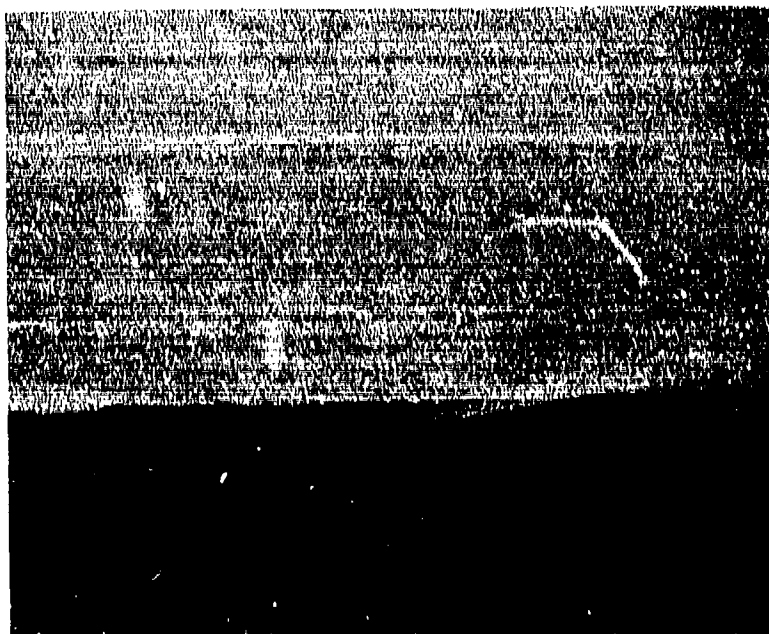
31

Figure 6.   Sensor Detection Envelope Visualization
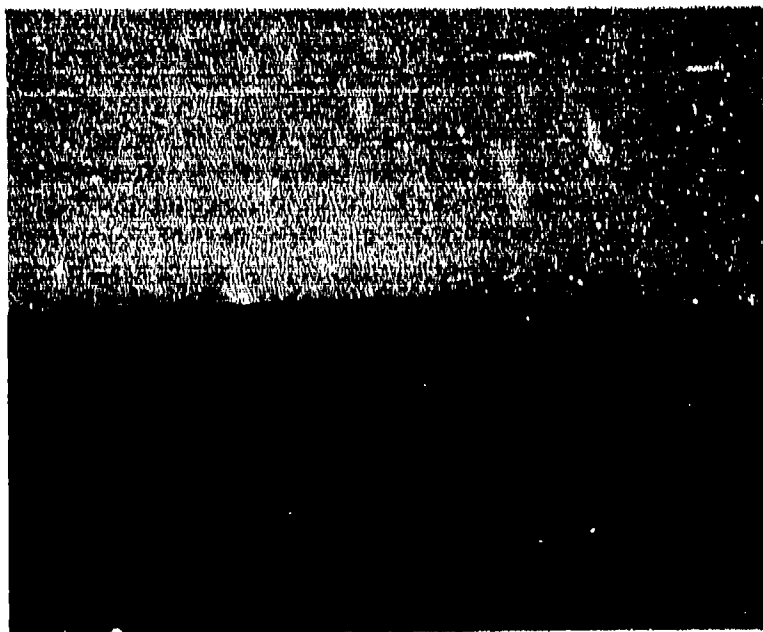

Figure 7.   Generic Head-Up Display

generic HUD is shown in figure 7. Since our prototype visualization system uses stereoscopic displays, we had to render the HUD stereoscopically. The question then arises, where in space should the HUD be placed? Placing the HUD at the same display position in both left and right eye views will position the HUD on the surface of the display screen, when viewed stereoscopically. By introducing a horizontal offset to either eye view, one can produce either positive or negative parallax, which will place the HUD image behind or in front of the display screen, respectively. We at first supposed that the HUD would look best imaged at the surface of the display screen, but this required the eyes to reconverge from the display screen to the terrain scene, creating an uncomfortable situation for the viewer. Experimentation showed that the best location for the HUD image is at a distance beyond the display screen corresponding to distant elements of the scene. This is consistent with actual HUD display equipment, which optically image the HUD at infinity. This condition allows the pilot to keep his eyes converged on his target, and read the HUD as well.

5.4 VISIBILITY ATTENUATION

Dust and moisture in the atmosphere scatter light, making objects appear greyer with greater distance. This "haze" effect is a strong depth cue that has been implemented by computer-image generators for years. This capability has only recently been added to some workstation models. Since our IRIS 4D/240GTX model does not support this function, we have developed a technique for efficiently rendering haze. This technique makes use of the hardware alpha buffer provided on these workstations. The alpha buffer is a set of bit planes that augment the RGB bit planes. The alpha buffer can be used for several purposes, but it is primarily used for color blending. In this case we wish to blend a haze color with the color of each pixel in the terrain scene. The relative proportions of haze color and object color depends on the distance of the pixel from the viewer, and is calculated according to the relation

$$\alpha = e^{-kd/v}$$

where $k = \log_e 2.0$ is an attenuation constant, d is the distance to the object, and v is the visibility distance. This calculation is calibrated so that the visibility of an object is attenuated by one half when the distance equals the visibility distance. For example, the statement "visibility is 10 km" in this context means that at 10 km, the visibility of an object is reduced by half.

As stated, this calculation would place an enormous computational burden on the workstation. We have simplified the procedure by calculating the distance to each object, such as a building, power transmission

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tower, or patch of terrain, only once. Since this is already required by the field-of-view calculation in the current prototype, this incurs no additional computation. The alpha blending factor is then calculated using the above formulation. This blending factor is applied to the entire object. After all objects in the terrain scene have been rendered, the entire frame is flooded with the haze color. Each pixel will accept an amount of the haze color in proportion to its alpha blending factor. Since the color blending operation requires more time than normal pixel filling, we save time by reserving the blending function to only once each frame. This leads to an acceptable approximation to haze, although if visibility is reduced too much, discontinuities in the haze function can be observed between nearby terrain patches. The final effect is illustrated by figure 8.

5.5 CARTOGRAPHIC DISPLAY

Although 3D perspective displays of out-the-window terrain scenes are effective for familiarizing one's self with an area, they do not replace the need for conventional 2D map displays. We have added an optional 2D, overhead "God's eye-view" display as a small viewport inset on the perspective display. This display helps to orient the user. This feature is shown in figure 9.

The cartographic display can be created from the same data base and display list used for the perspective scene. The only modifications required are for the rendering procedure. For the overhead view, the projection is changed from a perspective projection to an orthographic projection. The projection is arranged so that the center of the viewport is the current location, and north is oriented at the top of the screen. As the viewer proceeds through the scene, the map appears to slide within its viewport, so that the current position is always centered. It is also necessary to change the direction of illumination, which for sunlight in the northern hemisphere is always from a southerly direction, to come from a northerly direction. The reason for this change is that, perceptually, the sense of relief will be reversed if the light comes from below; the mountains will seem to be valleys, and vice versa. This is a consequence of a well-known psychological phenomenon of the mind's perception of shape from shading information.

The implementation presented here has the drawback that additional drawing time is required to render both the perspective view and the cartographic view. The time is not as much as doubled, however, because of the relatively small size of the cartographic viewport. An alternative implementation would be to maintain a separate, large map image, any small window of which could be transferred to the cartographic viewport using

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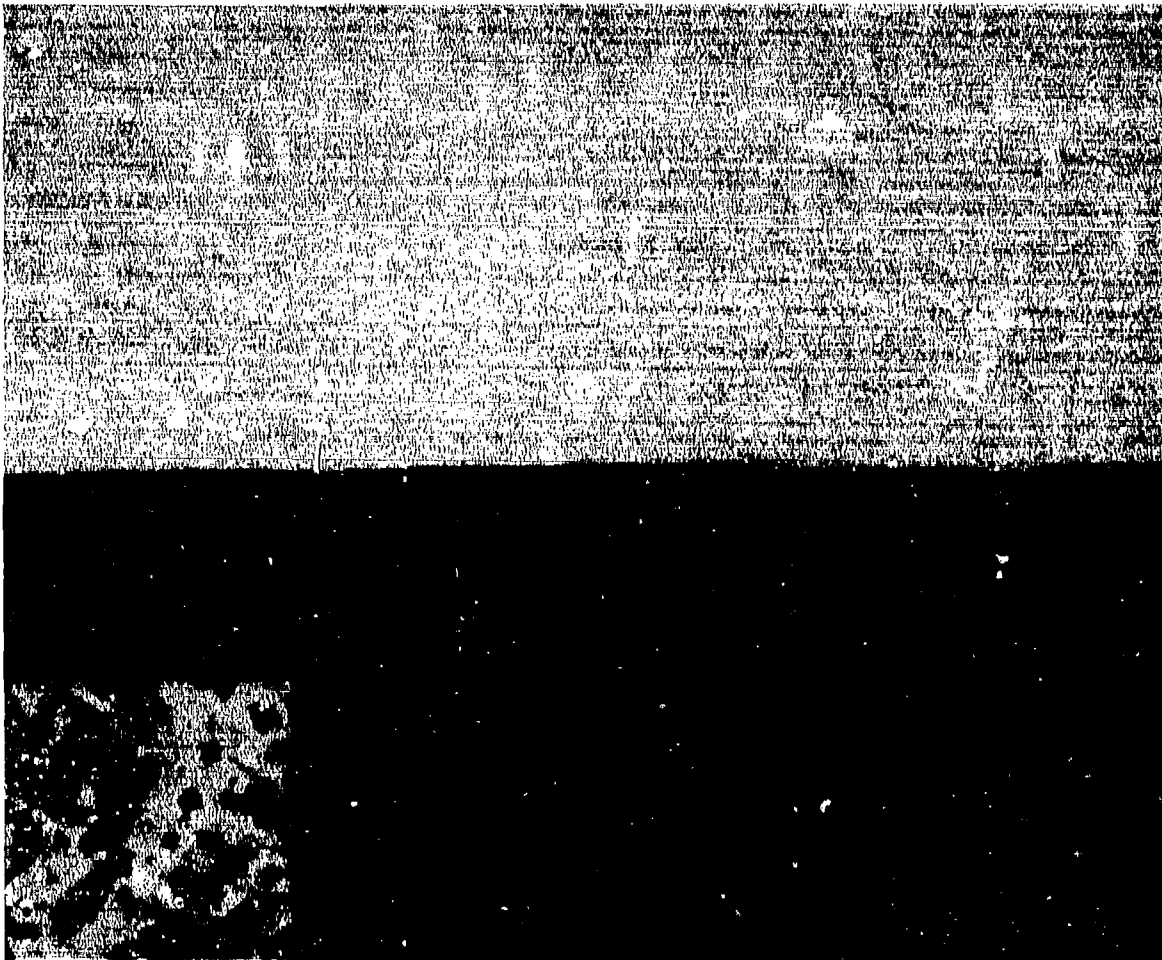Figure 8. Visibility Attenuation

Figure 9.   Cartographic Display Inset

fast bit block transfer instructions. Such an implementation could
provide faster response time, at the cost of more complexity.

5.6 VIEW FROM TARGET

We initially intended to provide another optional view, the view of
the aircraft approach from the target site. We considered this option the
lowest priority, however, because it does not demonstrate any new concepts
or clarify technical issues. It simply requires a change in viewpoint
coordinates and viewing direction. As of this report, it has not been
implemented.

5.7 PERFORMANCE

The prototype we described in [1] was hosted by an IRIS 4D/70GT
workstation. The version we describe here runs on an IRIS 4D/240GTX. The
principle difference between these models is that the 240 model contains
four 25 MHz microprocessors, whereas the 70 model had one 12.5 MHz pro-
cessor. The GTX graphics subsystem represents an incremental improvement
over the GT graphic subsystem. Unfortunately, the performance of our
prototype does not scale proportionally with clock speed, because the
program is now paced by the speed of the graphics processor subsystem. In
addition, this prototype makes no attempt to take advantage of the paral-
lelism that might be afforded by the four processors. The faster micro-
processor units did allow us to add most the features we described without
degrading performance seriously. We still maintain a 3 Hz to 4 Hz frame
update rate for full screen perspective views.

There is a noticeable performance degradation, however, when the
imagery insets cover a major portion of the perspective view display.
Considering the order of magnitude difference in numbers of polygons,
however, we consider the display update rate of .5 Hz to 1 Hz to be
acceptable.

SECTION 6

CONCLUSION

For terrain visualization applications requiring up 10 Hz to 15 Hz frame update rates, superworkstations can be used. Current limitations are antialiasing and texture capabilities, but these capabilities are available in the newest generation of workstations. Nominal smooth-shaded polygon rates exceeding 500,000/second are claimed for these workstations. Textured, antialiased polygons, however, will probably clock in at no more than 100,000/second. This performance level can support workstation-based, interactive terrain visualization fly-throughs of 3D geometry-based databases. While not applicable to training or full-fidelity simulations and rehearsals, this would be ideal for low-cost partial fidelity planning and rehearsal systems at the unit level.

Although provision must be made for integrating photographic imagery and photo-derived textures, imagery should not be the sole basis of design for a terrain visualization system. There are too many gaps in pure image data to present a consistent scene; namely, the sides of buildings and trees, the height or depth of cultural features, what is underneath trees or other camouflage. To add this information, one needs a detailed 3D synthetic database.

Instead of imagery fly-throughs, the fly-throughs should be of the synthetic database. The user could stop at any point and request a photo image from that viewpoint. The system then would select the best image available and transform it to the current viewpoint. If the image does not cover the field of view, it would be seen as an inset to the synthetic scene. The image should be stored in a compressed multi-resolution quadtree-like format, which would provide a method for dealing with antialiasing issues.

Notwithstanding the success our terrain visualization prototype has met to date, we propose to continue to enhance our prototype in the following areas.

a. Multiprocessing. Partitioned the current, single process into several independent, cooperating pipeline processes, to increase the overall image update rate.

b. Terrain Model. Improve the update rate, by reducing the number of polygons in a scene, and by optimizing the polygon fit to the terrain surface model.

c. **Aggregate Features.** Explore the possibility of dynamic instantiation of generic objects where statistical density data are available. This means forests populated with trees, and towns filled with buildings.

d. **Continuum of Levels of Detail.** Investigate advanced hierarchical data structures that will facilitate optimal use of display resources.

e. **Adaptive Complexity Management.** Dynamically trade-off scene quality versus update rates, in order to achieve a higher overall perception of scene detail and system responsiveness.

LIST OF REFERENCES

[1] Veron, H., D.A. Southard, J.R. Leger, and J.L. Conway, "3D Displays for Battle Management", RADC-TR-90-46, Rome Air Development Center, Air Force Systems Command, Griffiss Air Force Base, NY, April 1990 (DTIC AD-A223 142).

[2] Brady, J.T., "A Theory of Productivity in the Creative Process", *Computer Graphics and Applications*, Vol. 6, No. 3, May 1986, pp. 25-34.

[3] Schachter, B.J., *Computer Image Generation*, New York: John Wiley & Sons, 1983.

[4] Rich, H.H., "Trade Offs in Creating a Low-Cost Visual Simulator", *Proc. 11th Interservice/Industry Training Systems Conference*, Washington, DC, 13-16 Nov. 1989, pp. 214-223.

[5] Wyckoff, B.H., "Managing Cost/Performance Tradeoffs for Successful Visual Training", *Proc. 11th Interservice/Industry Training Systems Conference*, Washington, DC, 13-16 Nov. 1989, pp. 471-477.

[6] Evans & Sutherland, Simulation Division, Salt Lake City, UT, 1989; marketing brochures and calendar.

[7] General Electric Company, Simulation and Control Systems Department, Daytona Beach, FL, 1989; marketing brochures.

[8] Sogitech, Electronics Division, US Office, Wilmington, DE, 1989; marketing brochures.

[9] Star Technologies, Graphicon Products Division, Research Triangle Park, NC, 1989; marketing brochures.

[10] Megatek Corporation, San Diego, CA, 1989; marketing brochures.

[11] Rayson, J.K., J.W. Long, and J.S. Shelton, "Trip Report - Hughes Simulation Systems, Hughes Aircraft Company, and Naval Strike Warfare Center", Attachment to MITRE letter D62-L-203, 30-31 August 1989.

[12] Rogers, S.P, and V.A. Spiker, "Functional Capabilities of Mission Planning Systems: A Review of Features for Army Aviation Applications", Report No. 625-12, Contract No. DAAB07-85-C-F036, Tactical Information Systems Division, U.S. Army Avionics R&D Activity, Ft. Monmouth, NJ, June 1988.

41

[13] "DMG Today... The Map of Tomorrow", *The Bellringer*, Vol. XIV-I, Harris Corporation, Government Systems Sector, Melbourne, FL, January 1988, pp. 6-10; marketing literature and briefing.

[14] Pixar, San Rafael, CA, 1988; marketing brochures.

[15] Visual Technologies Incorporated, Plano, TX, 1989; marketing literature and briefing.

[16] Potmesil, M. and E.M. Hoffert, "The Pixel Machine: A Parallel Image Computer", *Computer Graphics (Proc. SIGGRAPH '89)*, Vol. 23, No. 3, July 1989, pp. 69-78.

[17] *IRIS Universe*, Silicon Graphics Inc., Mountain View, CA, 1989; a marketing magazine, contains many advertisements for various software packages.

[18] "Mission Simulator System Performance Specification", CTA Incorporated, I.C. Sim Division, Irvine, CA, 1989; marketing literature.

[19] "System Description for Image Perspective Transformation (OMNIVIEW)", ESL-88-0311, ESL Incorporated, Sunnyvale, CA, September 1988.

[20] Space Remote Sensing Center, Institute for Technology Development, NASA Stennis Space Center, MS; informational brochures and newsletters for Geographic Resources Analysis Support System (GRASS) software.

[21] Kasturi, R., R. Fernandez, M.L. Amlani, and Wu-chun Feng, "Map Data Processing in Geographic Information Systems", *Computer*, Vol. 22, No. 2, December 1989, pp. 10-21.

[22] Breden, W.O., and J.J. Zanoli, "Visualization of High-Resolution Digital Terrain", Master's Thesis, NPS52-89-38, Naval Postgraduate School, Monterey, CA, June 1989.

[23] Zyda, M.J., R.B. McGhee, R.S. Ross, D.B. Smith, and D.G. Streyle, "Flight Simulators for Under $100,000", *Computer Graphics and Applications*, Vol. 8, No. 1, Jan. 1988, pp. 19-27.

[24] Kaneda, K., F. Kato, E. Nakamae, T. Nishita, H. Tanaka, and T. Noguchi, "Three Dimensional Terrain Modeling and Display for Environmental Assessment", *Computer Graphics (Proc. SIGGRAPH '89)*, Vol. 23, No. 3, July 1989, pp. 207-214.

[25] Theimann, R., J. Fischer, G. Haschek, and G. Kneidl, "Visualisation of Digital Terrain Data", *Eurographics '89*, W. Hansmann, F.R.A. Hopgood, and W. Strasser, eds., North-Holland: Elsevier Science Publishers, 1989, pp. 17-195.

[26] Samet, H., "The Quadtree and Related Hierarchical Data Structures", *Computing Surveys*, Vol. 16, No. 2, June 1984, pp. 187-260.

[27] De Floriani, L., "A Pyramidal Data Structure for Triangle-Based Surface Description", *Computer Graphics and Applications*, Vol. 9, No. 2, March 1989, pp. 67-80.

[28] Cosman, M.A., "A System Approach for Marrying Features to Terrain", *Proc. 11th Interservice/Industry Training Systems Conference*, Washington, DC, 13-16 Nov. 1989, pp. 224-231.

[29] Tesser, H., A. D'Amico Beadon, L. Scarlatos, E. DeMund, "Requirements for Real-Time Three-Dimensional Display of Digital Cartographic Data", RADC-TR-89-107, Rome Air Development Center, Air Force Systems Command, Griffiss AFB, NY, August 1989.

[30] Crane, P.M., H.H. Bell, R.G. Kalinyak, J. Dooley, and D.C. Hubbard, "Simulation of Synthetic Aperature Radar I: Feature Density and Accuracy Requirements", AFHRL-TR-88-42, Operations Training Division, Air Force Human Resources Laboratory, Williams AFB, AZ, July 1989.

[31] Fagan, G.A., "Trip Report - Mission Rehearsal Conference", Attachment to MITRE letter D62-L-242, 27-28 September 1989.

[32] Clark, C.L., and T.C. Brown, "Photographic Texture and CIG: Modeling Strategies for Production Data Bases", *Proc. 9th Interservice/Industry Training Systems Conference*, Washington, DC, 30 Nov.-2 Dec. 1987.

[33] Kleiss, J.A., D.C. Hubbard, and D.G. Curry, "Effect of Three-Dimensional Object Type and Density in Simulated Low-Level Flight", AFHRL-TR-88-66, Operations Training Division, Air Force Human Resources Laboratory, Williams AFB, AZ, May 1989.

[34] Hall, R., *Illumination and Color in Computer Generated Imagery*, Springer-Verlag, 1989, pp. 45-62.

[35] Meyer, G.W., "Tutorial on Color Science", *The Visual Computer*, Vol. 2, 1986, pp. 278-290.

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Rome Laboratory plans and executes an interdisciplinary program in research, development, test, and technology transition in support of Air Force Command, Control, Communications and Intelligence (C^3I) activities for all Air Force platforms. It also executes selected acquisition programs in several areas of expertise. Technical and engineering support within areas of competence is provided to ESD Program Offices (POs) and other ESD elements to perform effective acquisition of C^3I systems. In addition, Rome Laboratory's technology supports other AFSC Product Divisions, the Air Force user community, and other DOD and non-DOD agencies. Rome Laboratory maintains technical competence and research programs in areas including, but not limited to, communications, command and control, battle management, intelligence information processing, computational sciences and software producibility, wide area surveillance/sensors, signal processing, solid state sciences, photonics, electromagnetic technology, superconductivity, and electronic reliability/maintainability and testability.